Search for Strong Gravity Signatures in Same-sign Dimuon Final States using the ATLAS detector at the LHC

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Abstract

A search for microscopic black holes has been performed in a same-sign dimuon final state using 1.3 fb^{-1} of proton-proton collision data collected with the ATLAS detector at a centre of mass energy of 7 TeV at the CERN Large Hadron Collider. The data are found to be consistent with the expectation from the Standard Model and the results are used to derive exclusion contours in the context of a low scale gravity model.

Keywords: LHC, ATLAS, microscopic black holes, extra dimensions, same-sign dimuons

1. Introduction

Models introducing extra dimensions can provide a solution to the hierarchy problem, the fact that the Planck scale $M_{\rm Pl} \sim 10^{16}$ TeV is much larger than the electroweak scale. In some models of extra dimensions, the gravitational field can propagate into $(n+4)$-dimensions, where n is the number of extra dimensions, while the Standard Model particles are restricted to four-dimensional space-time. Therefore, the gravitational field as measured in four dimensions is reduced in strength from the fundamental gravitational field. As a result, the Planck scale in $(n+4)$-dimensions $M_{\rm D}$ would be much smaller than the Planck scale in four dimensions $M_{\rm Pl}$, and possibly comparable to the electroweak scale. An example of such a model of extra dimensions is the ADD model, which is a model of large flat extra dimensions [1, 2, 3].

If extra dimensions exist and $M_{\rm D}$ is in the TeV range, microscopic black holes with masses at the TeV scale could be produced at the Large Hadron Collider [4, 5, 6, 7, 8]. Black holes are expected to be produced when the classical impact parameter of two colliding partons is smaller than the higher-dimensional horizon radius corresponding to a black hole with mass equal to the invariant mass of the colliding parton system. This paper considers higher-dimensional Schwarzschild solutions, as well as Kerr solutions for black holes with initial angular momentum equal to the relative angular momentum between the two colliding partons; parton spin is ignored [9].

The production of black holes at the LHC would occur with a continuous mass distribution ranging from approximately the reduced Planck scale M_{D} to the proton-proton centre of mass energy of 7 TeV. The classical approximations used for black hole production and the semi-classical approximations for decay are expected to be valid only for masses well above the higher-dimensional Planck scale. A lower threshold M_{TH} is thus applied to the black hole mass to reduce the contributions from regions where the models are invalid. The production cross section is set to zero if the parton-parton centre of mass energy is below M_{TH}.

Once produced, a black hole starts to evaporate in a manner described by Hawking radiation [10] which determines the energy and multiplicity distributions of the emitted particles. The relative multiplicities of the emitted particles are determined by the number of degrees of freedom of each particle type and the decay modes of emitted unstable particles. Black hole events should therefore have a high multiplicity of high-p_{T} particles which is the characteristic feature exploited in this analysis. Models with rotating and non-rotating black holes are considered in this paper. The multiplicity of high-p_{T} particles is lower for rotating black holes [11]. No graviton initial-state radiation or emission from the black hole is considered. As a result of the emission of Hawking radiation, the mass of the produced black hole decreases. When the mass of the black hole approaches M_{D}, quantum gravity effects become important. In the final stage of the black hole decay, the classical evaporation is no longer a good description. In such cases where the black hole mass is near the Planck scale, the burst model adopted by the BlackMax event generator [9, 12] is used to model the final part of the decay.

A search for microscopic black holes in a multijet final state is presented in Ref. [13]. In this analysis, events are selected containing two muons of the same charge. This channel is expected to have low Standard Model backgrounds while retaining good signal acceptance. Isolated muons (i.e. muons with very little activity around them in the detector) can be produced directly from the black hole or from the decay of heavy particles such as W or Z bosons. Muons from the semi-leptonic decays of heavy-flavour hadrons produced from the black hole can have several other particles nearby and can therefore be non-isolated. In order to maintain optimal acceptance for a possible signal, only one of the muons is required to be isolated in this analysis, thereby typically increasing the acceptance in the signal region by 50%.

The decay of the black hole to multiple high-p_{T} objects is used to divide the observed events into background-rich and potentially signal-rich regions. This is done by using the number of high-p_{T} charged particle tracks as the criterion to assign events to each region. As will be quantified below, black hole events typically have a high number of tracks per event (N_{trk}), while Standard Model processes have sharply falling track multiplicity distributions. In the background-rich region, where only small signal contributions are expected, data and Monte Carlo simulations are used to estimate the number of events after selections. This background estimate is validated by comparing to data. The expected number of events from Standard Model processes in the signal-rich region is then compared with the measured number, and a constraint on the contribution from black hole decays is inferred.

The backgrounds from Standard Model processes are divided into two categories: processes where the two muons come from correlated decay chains and processes that produce same-sign dimuons in uncorrelated decay chains. Same-sign dimuon events in correlated decay chains are produced primarily in the decays of $t\bar{t}$ events and $b\bar{b}$ events. In $t\bar{t}$ events, the most likely case is that the leading isolated muon arises from the decay of a W-boson from one of the top-quarks, and the other muon of same charge comes from the semileptonic decay of a b-quark from the other top-quark. In $b\bar{b}$ events, the leading muon arises from the semileptonic decay of one b-quark, and the other muon from the sequential decay $b \to cX \to \mu X'$. Same-sign dimuons can also be produced due to $B^0\bar{B}^0$ mixing. The backgrounds from $t\bar{t}$ and $b\bar{b}$, and those from gauge boson pair production such as WZ are estimated from Monte Carlo samples.

Dimuon events in uncorrelated decay chains arise predominantly from the W+jets process, where the leading isolated muon comes from W-boson decay and the other muon from a π/K decay-in-flight, or the semi-leptonic decay of a b or c hadron in the remainder of the event. This background also has contributions from the Z+jets process, and from low-p_{T} dijet events. The background from uncorrelated decay chains is estimated from data. In the signal-rich region, the dominant backgrounds come from $t\bar{t}$ events and from muons produced in uncorrelated decays.

The rest of this paper is organised as follows. After a brief description of the ATLAS detector in Section 2, the data set and Monte Carlo samples are described in Section3. The event selection and the procedures to determine the backgrounds and their uncertainties are explained in Section 4 and 5 respectively. The results and their interpretation are discussed in Section 6.

2. The ATLAS Detector

The ATLAS detector [14] covers nearly the entire solid angle* around the collision point with layers of tracking detectors, calorimeters and muon chambers. The inner detector is immersed in a 2 T magnetic field along the z-axis and provides charged particle tracking in the range $|\eta| < 2.5$. The silicon pixel detector covers the vertex region and typically provides three measurements per track, followed by the silicon microstrip tracker (SCT) which provides measurements from eight strip layers. The silicon detectors are complemented by the transition radiation tracker (TRT) which provides more than 30 straw-tube measurements per track and improves the momentum resolution.

*ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis coinciding with the axis of the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r,ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe, referred to the x-axis. The pseudorapidity is defined in terms of the polar angle θ (with respect to the z-axis) as $\eta = -\ln \tan(\theta/2)$.

The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. Lead-liquid argon (LAr) electromagnetic sampling calorimeters cover the range $|\eta| < 3.2$, with an additional thin LAr presampler covering $|\eta| < 1.8$ to correct for energy loss in material upstream of the calorimeters. Hadronic calorimetry is provided by a scintillator-tile calorimeter over $|\eta| < 1.7$ and two copper/LAr endcap calorimeters over $1.75 < |\eta| < 3.2$. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeters for electromagnetic and hadronic measurements respectively up to $|\eta| < 4.9$.

The muon spectrometer consists of separate trigger and high-precision tracking chambers which measure the deflection of muon tracks in a magnetic field with a bending integral of approximately 2 to 8 Tm. The magnetic field is generated by three superconducting air-core toroid magnet systems. The tracking chambers cover the region $|\eta| < 2.7$ with three layers of monitored drift tubes and cathode strip chambers in the innermost region of the endcap muon spectrometer. The muon trigger system covers the range $|\eta| < 2.4$ with resistive plate chambers in the barrel, and thin gap chambers in the endcap regions.

3. Data and Monte Carlo Samples

The data used in this analysis were collected between March and July 2011 at the LHC operating at a centre of mass energy of 7 TeV. The total integrated luminosity after detector and data-quality requirements is 1.3 fb^{-1}, with an uncertainty of 3.7% [15, 16]. The data were recorded with a single muon trigger with the threshold at 20 GeV on the muon's transverse momentum. The muon trigger efficiency reaches the plateau regime for transverse momenta above 25 GeV. The plateau efficiency is 75% in the barrel and 88% in the endcap for muons reconstructed offline. In this analysis it is required that at least one of the selected muons with p_{T} above 20 GeV matches the trigger criteria. During the considered data-taking period, the LHC configuration was such that the mean number of primary proton-proton interactions per bunch crossing was close to 6. The effect of this "pile-up" is taken into account in the analysis.

Several Monte Carlo samples are used both for signal modelling and background estimation. These samples are processed with the ATLAS full detector simulation [17] which is based on the GEANT4 toolkit [18]. The simulated events are then reconstructed with the same software chain as the data. The effect of pile-up is modelled by overlaying simulated minimum bias events onto the original hard-scattering event. Monte Carlo events are then re-weighted so that the reconstructed vertex multiplicity distribution agrees with the data.

Background Monte Carlo samples are generated for $t\bar{t}$, as well as for $b\bar{b}$ and $c\bar{c}$ processes. The latter are considered together in the following and referred to as b/c for simplicity. The $t\bar{t}$ events are generated with MC@NLO [19, 20] with an assumed top-quark mass of 172.5 GeV, and with the next-to-leading order CTEQ66 [21] parton distribution function (PDF) set. Fragmentation and hadronisation of the events is done with Herwig [22] using Jimmy [23] for the underlying event model. The b/c Monte Carlo sample is generated and hadronised with Pythia [24] using the ATLAS AMBT1 tune [25]. It is produced with a filter at the generator level requiring two muons with $p_{\mathrm{T}} > 10$ GeV each. The diboson samples (WZ and ZZ) are generated with HERWIG. They are filtered to have at least one electron or muon with $p_{\mathrm{T}} > 10$ GeV. The single top background in the Wt channel is estimated with ACERMC [26]. The single top backgrounds in the $t-$channel and $s-$channel are included in the background estimate derived from data. The b/c, diboson and single top samples are all generated using the MRST2007 PDF [27]. Samples of W+jet and Z+jet events produced using Alpgen [28] are also used for cross-checks.

Signal Monte Carlo samples are generated using BLACKMAX 2.01 and hadronised with PYTHIA using the ATLAS AMBT1 tune. The samples are produced with the CTEQ66 PDF set with the mass of the black hole used as the QCD scale. For the signal samples, M_D is varied between 0.5 TeV and 2.5 TeV and M_{TH} is varied between 3 TeV and 5 TeV. In each case, samples are generated with 2, 4 and 6 extra dimensions.

4. Event Selection

Events passing the single muon trigger are required to have at least one primary vertex with at least five associated tracks with $p_{\mathrm{T}}^{\mathrm{track}} > 400$ MeV. If the event has multiple primary vertices, the vertex with the largest $\sum(p_{\mathrm{T}}^{\mathrm{track}})^2$ is identified as the "hard-scattering vertex".

Tracks found in the inner detector (ID) are selected using the following criteria:

$$p_{\mathrm{T}}^{\mathrm{track}} > 1 \ \mathrm{GeV}, \ N_{\mathrm{pixel}} \geq 1, \ N_{\mathrm{SCT}} \geq 6,$$
$$|\eta| < 2.4, \ |d_0| < 1.5\,\mathrm{mm}, \ |z_0 \sin\theta| < 1.5\,\mathrm{mm},$$

where N_{pixel} and N_{SCT} are the number of hits[†] from the pixel and the SCT detectors, respectively, that are associated with the track, and d_0 and z_0 are the transverse and longitudinal impact parameters measured with respect to the hard-scattering vertex. Muon candidates are reconstructed from tracks measured in the muon spectrometer (MS). The MS tracks are then matched with ID tracks using a procedure that takes material effects into account. The parameters for the resulting matched muon candidates are obtained by a statistical combination of the measurements in the MS and the ID.

At least two muons passing these selections are required in each event. Both must come from the hard-scattering vertex and satisfy $|\eta| < 2.4$. The muon with the highest transverse momentum is required to have $p_{\mathrm{T}} > 25$ GeV. This leading muon is also required to be isolated by requiring that the sum of transverse momenta of ID tracks in a cone in $\eta - \phi$ space of radius $\Delta R = 0.2$ around the muon is less than $0.2{\times}p_{\mathrm{T}}$ of the muon. The muon with the next highest transverse momentum is required to have $p_{\mathrm{T}} > 15$ GeV and the same charge as the leading muon. No isolation requirement is made on this second muon.

[†]A hit is a signal above threshold in a particular detector element.

The two muons are required to satisfy $\Delta R > 0.2$ to explicitly ensure that the isolated muon is not close to the second muon. The leading muon is required to have small impact parameter significance by imposing $|d_0/\sigma(d_0)| < 3$. The impact parameter is calculated with respect to the hard-scattering vertex in the event.

The track multiplicity is constructed by counting the number of ID tracks associated to the hard-scattering vertex which satisfy $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 2.4$. By definition, the track count includes the two muon candidates. A signal-rich region is defined by selecting events with at least ten such tracks, while events with less than ten tracks are used to validate the prediction of the expected backgrounds.

All selections except the trigger are applied to the Monte Carlo events. To account for the trigger efficiency, the Monte Carlo events are weighted with the efficiency measured from data, while the differences in muon reconstruction and identification between data and simulation are accounted for by applying p_{T} and η dependent scale factors [29, 30] to the Monte Carlo events when calculating the acceptance. This is important when the sub-leading muon provides the trigger as the trigger efficiency varies with p_{T} in the region between 20 and 25 GeV.

The tracking efficiency in data is well reproduced by the Monte Carlo simulation [31]. This is confirmed by additional studies of tracking performance in a dense environment [32]. No corrections to the Monte Carlo are therefore applied.

5. Background Estimation

The two components of the background from correlated and uncorrelated particle decays are determined using a mixture of Monte Carlo simulation and techniques using data.

5.1. Correlated Background Estimates

The correlated background arises from processes such as $t\bar{t}$ production where, for example, the isolated muon comes from top decay ($t \to bW \to b\mu\nu$) and the other (non isolated) from the antitop decay ($\bar{t} \to W\bar{b} \to W\mu\nu\bar{c}$). The background from $t\bar{t}$ production is estimated from Monte Carlo simulation. The approximate next-to-next-to-leading-order production cross section of 165 pb [33, 34, 35] is used to normalise the Monte Carlo prediction. This cross section is in agreement with the measurement of the $t\bar{t}$ cross section at ATLAS [36]. The sources of systematic uncertainty on the $t\bar{t}$ background described in Ref. [37] are considered and the uncertainty from each source is shown in Table 1. The sources considered are the choice of generator, the amount of initial and final state radiation (ISR/FSR), the top-quark mass, and the theoretical uncertainty on the predicted production cross section. The largest contribution to the uncertainty is 9.6% on the cross section which arises from variations in the renormalisation and factorisation scales (5.6%) and the PDF uncertainty (4%). The

Source	Muon+fake (%)	$t\bar{t}$ (%)	b/c (%)	Signal (%)
Measurement statistics	4.1			
Subtraction of $t\bar{t}+b/c+Wt$+diboson	20			
ISR/FSR		7.1		
t-quark mass		4.5		
Cross section		$^{+7}_{-9.6}$		
Monte Carlo Generator		5.1		
Luminosity		3.7		3.7
μ reco/trig		2.6		1.5
PDF(Acceptance)				3.0
Rescaled Truth Acceptance				14.3
Ratio (nominal/inverted)			8.5	
Extrapolation to $N_{\mathrm{trk}} \geq 10$			100	
Total uncertainty	20.4	14.4	100.4	15.1

Table 1: Systematic uncertainties in percent on the background and signal estimates in the signal region from various sources. μ reco/trig stands for the uncertainty due to trigger efficiency and muon reconstruction efficiency scale factors applied to the Monte Carlo events. A blank entry indicates that the particular systematic uncertainty does not apply to that particular background.

uncertainty due to the choice of generator is evaluated by comparing the predictions of MC@NLO with those of POWHEG [38] interfaced to PYTHIA. The POWHEG samples are generated using the MRST2007 PDF set. The uncertainty due to the top-quark mass is obtained by generating $t\bar{t}$ samples with top mass ± 2.5 GeV from the nominal choice of 172.5 GeV. The ISR/FSR uncertainty is determined by using the ACERMC generator interfaced to PYTHIA, and by varying the ISR and FSR Λ_{QCD}, and the ISR and FSR cutoff. There is also an additional 2.6% uncertainty on the $t\bar{t}$ estimate from trigger weight and muon reconstruction efficiency scale factors.

The background from b/c production is estimated in two steps. In the first step, the background is determined in the $N_{\mathrm{trk}} < 10$ (background) region using a heavy-flavour enriched data sample to normalise the Monte Carlo prediction. In the second step, the estimated background is extrapolated from $N_{\mathrm{trk}} < 10$ to $N_{\mathrm{trk}} \geq 10$ using Monte Carlo.

To estimate b/c production in the background region, a heavy-flavour rich sample is selected by inverting the isolation and impact parameter significance requirements on the leading muon. This yields 6480 events. The b/c Monte Carlo sample is used to measure the ratio of events passing the nominal muon selection to those passing the inverted selection. The ratio is 0.33 ± 0.03 where the uncertainty comes from the limited size of the Monte Carlo sample. Applying this ratio to the heavy-flavour rich sample in data gives the b/c estimate in the background region. The shapes of the kinematic distributions for the b/c background, such as p_{T} of the muons are also obtained from the heavy-flavour rich sample.

The $N_{\rm trk}$ distribution in the Monte Carlo is then fit with an exponential to determine the fraction of events with $N_{\rm trk} \geq 10$. The method is validated by varying the fit range, testing the extrapolation procedure in the $t\bar{t}$ Monte Carlo, as well as by relaxing the $p_{\rm T}$ requirements on the muons to enhance the statistics of the b/c Monte Carlo. Based on these studies, a 100% systematic uncertainty due to the extrapolation is assigned to the b/c background in the signal region.

The backgrounds from diboson (WZ, ZZ) and single-top processes are estimated from the corresponding Monte Carlo samples and are found to be negligible.

5.2. Uncorrelated Background Estimate

The uncorrelated background arises when the second muon is not a true muon (fake), or is a muon from K or π decay, or from events where there is no correlation between the production mechanisms of the two muons. The background from uncorrelated decays is estimated by first measuring the probability for a track to be reconstructed as a muon in a control sample from data. This 'fake' probability is then applied to data events with one muon and one or more tracks to obtain a prediction for μ+fake dimuon events.

The control sample consists of W-boson + track events. Events are selected with at least one isolated muon with $p_{\rm T} > 25$ GeV and missing transverse momentum ($E_{\rm T}^{\rm miss}$) satisfying 25 GeV $< E_{\rm T}^{\rm miss} <$ 80 GeV. $E_{\rm T}^{\rm miss}$ is constructed from the sum of all cells contained in calorimeter clusters and is corrected for the presence of muons in the event. The transverse mass calculated from the muon and the $E_{\rm T}^{\rm miss}$ is required to be between 50 GeV and 120 GeV. These events are also required to have at least one track in addition to the muon, with $p_{\rm T} > 15$ GeV and the same charge as the muon. If an event has more than one such track, then all tracks are considered for the measurement. The events are also required to have less than ten tracks to remove possible signal contributions.

A subset of the W-boson + track control sample is then selected by requiring an additional muon passing the analysis selection criteria with $p_{\rm T} > 15$ GeV and of the same charge as the first selected muon. Using this subset, the fraction of events where a second muon is present is determined directly from data. This fraction contains contributions from fakes, K or π decay, and heavy-flavour decays. To avoid double-counting, the contributions from the correlated decays from $t\bar{t}$, b/c, and diboson processes are estimated from Monte Carlo (as described) and subtracted. The per-track rate is measured in three $p_{\rm T}$ bins; for $p_{\rm T} < 20$ GeV the rate is $(4.4 \pm 0.2) \times 10^{-3}$, for $20 < p_{\rm T} < 60$ GeV the rate is $(3.7 \pm 0.1) \times 10^{-3}$, and for $p_{\rm T} > 60$ GeV the rate is $(3.7 \pm 2) \times 10^{-3}$. This rate is applied to all events in data with one muon and at least one track of the same charge with $p_{\rm T} > 15$ GeV. If more than one track is found, then each track is considered in calculating a total probability for the event to be reconstructed as a dimuon event. The uncertainty on the background estimate from the nominal fake rate measurement due to measurement statistics is 4.1%.

Process	Events
b/c	2120 ± 30(stat) $\pm$ 200(syst)
$t\bar{t}$	750 ± 100(syst) $\pm$ 30(lumi)
μ+fake	1300 ± 2(stat) $\pm$ 260(syst)
Wt	53 ± 2(syst)
$WZ + ZZ$	36 ± 1(syst)
Predicted	4270 ± 30(stat) $\pm$ 340(syst)
Observed	3775

Table 2: Numbers of expected and observed events in the background-rich control region with $N_{\mathrm{trk}} < 10$. Only the uncertainties due to the limited size of the Monte Carlo samples are included for the diboson ($WZ + ZZ$) and single-top (Wt) backgrounds.

To determine the systematic uncertainty, shown in Table 1, the amount of subtracted $t\bar{t} + b/c + Wt$+diboson background is varied up and down by 1σ. The corresponding variation in the fake estimate is 20% which is taken as the systematic uncertainty on this background.

This method is verified by using the W+jet and single-top Monte Carlo samples as pseudo-data to measure the rate and then make a prediction. Similar studies on fake muon probability, with different selection criteria, are reported in Ref. [39] and show consistent results.

The background estimation is tested in events with the same selections as the signal region except the track multiplicity which is required to be $N_{\mathrm{trk}} < 10$. The prediction from the Standard Model is shown in Table 2, along with the number of observed events in data in the background region. The contribution from the signal in the background region has been checked to be less than 0.1% of backgrounds for various choices of the signal parameters. The event rates observed in the background region agree with the prediction within the uncertainties.

6. Results and Interpretation

Figures 1 and 2 show the p_{T} distributions of both muons and the track multiplicity in all same-sign dimuon events respectively before applying the N_{trk} requirement. The prediction for a sample signal model for non-rotating black holes with $M_{\mathrm{D}} = 800$ GeV, $M_{\mathrm{TH}} = 4$ TeV, and six extra dimensions is also shown. Good agreement is observed between the measured distributions and the background expectations. As shown in Figure 2, the backgrounds peak at low values of the track multiplicity while a possible signal has a higher number of tracks. Table 3 shows the expected and observed numbers of same-sign dimuon events in the signal region. No excess over the Standard Model predictions is observed in the data.

The background in the signal region is dominated by the $t\bar{t}$ and by the uncorrelated decays from W+jet events. The relative contributions of the various backgrounds are different in the background-rich (Table 2) and signal-rich

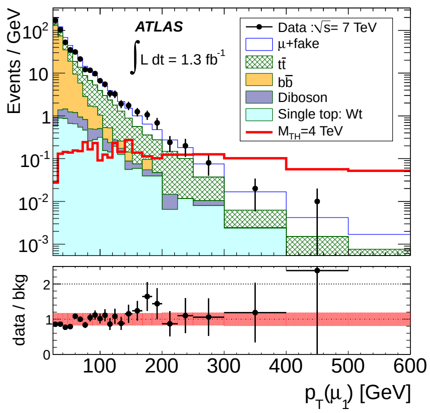

Figure 1: The leading (left) and sub-leading (right) muon p_{T} distributions for same-sign dimuon events before the N_{trk} cut. The background histograms are stacked. The signal expectation for a non-rotating black hole model with parameters $M_{\mathrm{D}} = 800$ GeV, $M_{\mathrm{TH}} = 4$ TeV, and six extra dimensions is overlaid for illustrative purposes. The bottom panels show the ratio of data to the expected background (points) and the total systematic uncertainty on the background (shaded area).

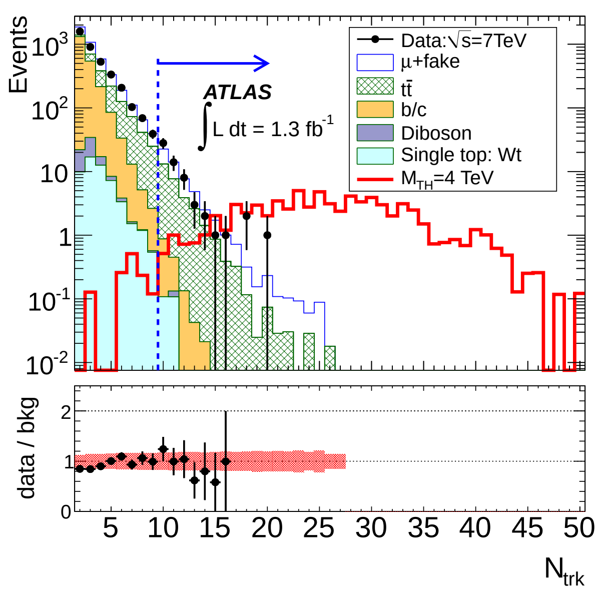

Figure 2: The track multiplicity distribution for same-sign dimuon events. The region with $N_{\mathrm{trk}} \geq 10$ is selected as the signal region. The background histograms are stacked. The signal expectation for a non-rotating black hole model with parameters $M_{\mathrm{D}} = 800$ GeV, $M_{\mathrm{TH}} = 4$ TeV, and six extra dimensions is overlaid for illustrative purposes. The bottom panel shows the ratio of data to the expected background (points) and the total systematic uncertainty on the background (shaded area).

(Table 3) regions. In particular the b/c contribution falls more rapidly with increasing N_{trk} than the other backgrounds and is very small in the signal-rich region. By removing the isolation requirement on the leading muon, the distribution is dominated by b/c background and the Monte Carlo simulation agrees with data giving confidence in the b/c prediction.

Process	Events
b/c	0.77 ± 0.77(syst)
$t\bar{t}$	29.2 ± 4.1(syst) ± 1.1(lumi)
μ+fake	25.6 ± 0.3(stat) ± 5.2(syst)
Other backgrounds	0.25 ± 0.11(syst)
Predicted	55.8 ± 0.3(stat) ± 6.7(syst) ± 1.1(lumi)
Observed	60
Signal $M_{TH} = 4$ TeV	72.1 ± 4.5(syst)

Table 3: Number of expected and observed events in the signal region, like-sign dimuon events with $N_{\mathrm{trk}} \geq 10$. The other backgrounds are from diboson and single-top processes. The signal expectation for a non-rotating black hole model with $M_{\mathrm{D}} = 800$ GeV, $M_{TH} = 4$ TeV, and six extra dimensions is also shown.

Using the number of events observed in data and the background expectations, upper limits are set on $\sigma \times BR \times A$, where σ is the cross section, BR the branching ratio to dimuons, and A the acceptance of non Standard Model contributions in this final state in the signal region. The CLs method [40] is used to derive these limits assuming Gaussian uncertainties on the predicted background and signal, and Poissonian fluctuations on the observed number of events. The observed 95% confidence level upper limit on $\sigma \times BR \times A$ is 0.018 pb. This result is compatible with the expected limit of 0.016 pb, which is determined from pseudo-experiments using simulation. The 1σ and 2σ ranges on the expected limit are from 0.012 to 0.022 pb and from 0.008 to 0.029 pb respectively. The $BR \times A$ for the signal model shown in Table 3 is 3%, and typically varies between 1% and 6% for the signal models considered here.

Limits on the reduced Planck mass (M_{D}) and the minimum mass of the black hole (M_{TH}) for several models are set using the BlackMax generator and the CTEQ66 PDF. The signal yield is affected by the PDF choice due to two distinct effects: the change in the production cross section and the change in signal acceptance. The signal cross section obtained from MRST2007 is typically 40% to 50% higher than that from CTEQ66 for $M_D = 1$ TeV, $M_{TH} = 4$ TeV. This difference is somewhat larger than the uncertainty on the cross section from the CTEQ66 PDF error sets. At the large values of M_{TH} near the quoted limits, the invariant mass of the incoming partons is large and the PDFs are therefore used in a range of parton momentum fraction x where they are not well constrained. The theoretical uncertainty on the production cross section is potentially very large. For these reasons, no theoretical uncertainty on the signal cross section is assigned, that is, the exclusion limits are set for the exact benchmark models as implemented in the BlackMax generator: using

CTEQ66 rather than MRST2007 gives a more conservative limit. The cross section for the signal point shown in Table 3 is 2.1 pb. The uncertainty on the signal acceptance from the choice of PDF is estimated to be 3% by using the 44 error sets of the CTEQ66 PDF and is a small contribution to the overall uncertainty.

The observed results are used to obtain exclusion contours in the plane of M_{D} and M_{TH}. For a large number of points in the $(M_{\mathrm{D}}, M_{\mathrm{TH}})$ plane, the signal acceptance is measured using kinematic properties obtained from the event generator (truth). This truth level acceptance is compared to the acceptance from full detector simulation for a smaller set of points which are representative of the model parameters probed in this analysis. To account for the difference in acceptances, the truth level acceptance is scaled by a constant factor of 0.7 ± 0.1 which is determined by comparing truth to fully simulated points. Therefore the uncertainty on the signal prediction consists of the following components: the uncertainty due to rescaling of truth acceptance, the uncertainty on the luminosity of the data sample, the uncertainty on acceptance due to the PDF, the experimental uncertainty on acceptance due to muon trigger and identification efficiencies and a statistical uncertainty due to the finite Monte Carlo samples (see Table 1).

Figure 3 shows the expected and observed exclusion contours for rotating and non-rotating black holes for 2 and 6 extra dimensions. The non-smoothness of the exclusion contours reflects the discrete nature of the Monte Carlo grid in the $(M_{\mathrm{D}}, M_{\mathrm{TH}})$ plane and the finite Monte Carlo statistics at the generated points. Lines of constant slope $(M_{\mathrm{TH}}/M_{\mathrm{D}})$ of 3, 4 and 5 are also shown in the figure. The semi-classical approximations used for black hole production and decay are expected to be valid only for large slopes. It can be seen that if this ratio is greater than three, the limit on M_{TH} is larger than half the centre-of-mass energy.

In view of the rapidly falling PDF's in this region, further significant improvements on these limits are not expected until the LHC energy is increased. For example, moving from $M_{\mathrm{TH}} = 4.7$ TeV to $M_{\mathrm{TH}} = 5$ TeV changes the signal cross section from 0.24 pb to 0.06 pb (for non-rotating black holes in models with $M_{\mathrm{D}} = 500$ GeV and six extra dimensions). It is also worth noting that the exclusion contours are dependent on the model considered, and this analysis is not expected to be sensitive to black hole models with decays to low multiplicity final states such as quantum black holes [41].

In summary, a search for extra dimensions in the same-sign dimuon final state has been performed using 1.3 fb^{-1} of data recorded with the ATLAS detector in 7 TeV proton-proton collisions at the LHC. No excess of events over the Standard Model prediction is observed and exclusion contours are obtained in the plane of the reduced Planck scale M_{D} and the threshold M_{TH} for black hole production. A model independent limit of 0.018 pb on any new physics contribution in the signal region with the described selection is set.

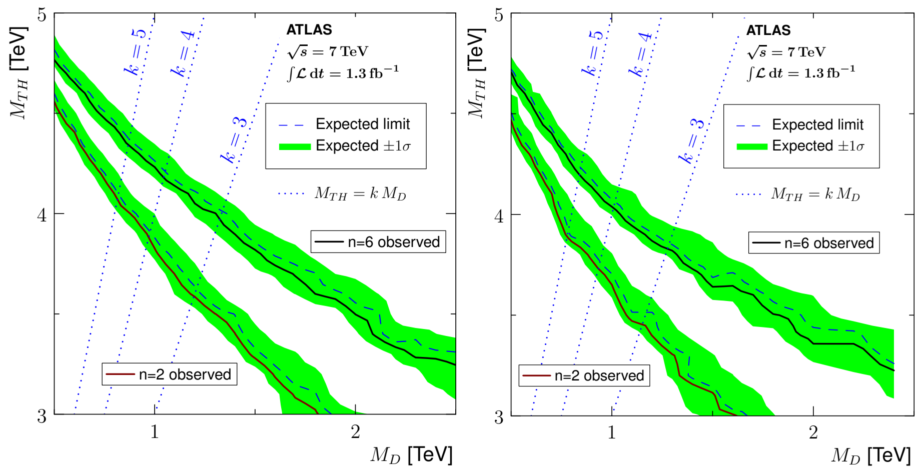

Figure 3: 95% confidence level exclusion contours for non-rotating (left) and rotating (right) black holes in models with two and six extra dimensions. The dashed lines show the expected exclusion contour with the 1σ uncertainty shown as a band. The solid lines show the observed exclusion contour. The regions below the contour are excluded by this analysis. The dotted lines show lines of constant slope equal to 3, 4, and 5. Only slopes much larger than 1 correspond to physical models.

7. Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; ARTEMIS, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA

(Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

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